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Effect of Regenerative Agriculture on Soil Health, Ecosystem Services and Economic Performance in a Commercial Olive Orchard in Southern Spain

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ABSTRACT

Regenerative agriculture (Reg) improves soil health, ecosystem services and economic performance, but its impact on olive groves remains underexplored. This study evaluates soil physical, chemical and biological properties, ecosystem services and economic outcomes in adjacent regenerative (Reg) and conventional (Conv) olive groves in southern Spain. After 6 years, Reg sites showed substantial improvements: water-stable aggregates (+ 33%), soil moisture at field capacity (+ 33%), soil organic matter (+ 75%), extractable potassium (+ 46%) and culturable microbial populations (+ 18%) relative to Conv. Some indicators approached values of a nearby forest reference, for example, soil organic matter 5.9% versus 13.5% and Shannon microbial diversity 3.4 versus 3.4. Leaf nutrient concentrations were adequate in both groves, although nitrogen and phosphorus were near lower recommended thresholds. Areas with reduced vegetation cover in the Reg grove (RegB) had lower soil health indicators but remained comparable to Conv. Soil organic carbon stock was highest in RegG (7.9 Mg ha^{-1}) and similar in RegB (5.3 Mg ha^{-1}) and Conv (5.6 Mg ha^{-1}). Regenerative management enhanced ecosystem services across all categories, particularly regulating and cultural services, while provisioning services were maintained. Economically, RA achieved higher gross income (2825 € vs. 2428 € per ha), net balance income (1340 € vs. 467 € per ha) and a superior B:C ratio (1.90 vs. 1.40) compared to Conv. These findings demonstrate that Reg improves soil functionality, supports multiple ecosystem services and increases economic returns, highlighting the importance of regenerative practices in olive groves.

1 | Introduction

Cultivated olive (*Olea europaea* subsp. europaea) is one of the most widespread woody crops worldwide and holds major historical importance in the Mediterranean region (Infante-Amate et al. 2014). Its origins date back to 3000 and 4000 years BC in the region of Palestine, although its main cultivation area has been the Mediterranean Basin (Barranco Navero et al. 2017). Currently, olive cultivation covers about 11.1 Mha worldwide, with approximately 81% concentrated in the Mediterranean region (FAOSTAT 2025). Spain is the world's leading olive producer, accounting for approximately 28% of global production (average 2019–2023) across 2.7 Mha (FAOSTAT 2025).

The olive sector is characterised by its international scope and technical-commercial dynamism, having undergone significant transformations in recent decades, mainly due to technological innovations such as the expansion of deficit irrigation and harvest mechanisation, a growing consumption of oil (IOC 2025) and a growing societal demand for sustainable and environmentally friendly production systems. Because olive trees are cultivated under highly diverse edaphoclimatic and social conditions and have long life spans, production systems are extremely heterogeneous. These range from ancient, low productivity extensive orchards yielding less than 1000 kg $ha^{-1}yr^{-1}$ to highly intensified orchards with very high productivity above 10,000 kg $ha^{-1}yr^{-1}$ (Guzmán et al. 2020).

In many Mediterranean mountainous areas, olive cultivation faces numerous environmental and socioeconomic challenges. In regions where olive growing is traditional, depopulation and land abandonment are major concerns. These problems are often exacerbated in mountainous terrain, where soil degradation and reduced profitability prevail. Soil degradation caused by accelerated erosion, exacerbated by inappropriate management on steep slopes, represents a serious concern (Gómez et al. 2011; Rodríguez Sousa et al. 2019), with significant economic impacts (Panagos et al. 2018). Underlying causes include low profitability, limited infrastructure and technology, low mechanisation and limited competitiveness in global markets (De Graaff et al. 2007; Stillitano et al. 2018). This situation undermines rural economies, increases environmental vulnerability and threatens the viability of family farms due to high management and harvesting costs on steep slopes. Additionally, climate change directly affects the yield and productivity of olive groves. In response to these challenges, an increasing number of farmers are adopting organic production systems and regenerative agriculture practices aimed at restoring soil fertility, enhancing water retention, increasing biodiversity, reducing dependence on external inputs and strengthening farm resilience to climate variability. These factors are essential to maintain productivity and ensure the long-term viability of olive cultivation in mountainous and marginal regions.

In Spain, these initiatives receive partial support through national or regional agro-environmental programs, including the CAP (Common Agricultural Policy) eco-schemes and certain sustainability subsidies implemented by autonomous communities. However, direct support specifically for regenerative agriculture remains limited. To fulfil this potential, there is a growing consumer demand for certification systems that verify sustainability improvements (Polenzani et al. 2020). However, while organic farming is well recognised and regulated, regenerative agriculture lacks a consistent certification framework, making scientific evidence on its benefits particularly important for future policy design and market recognition.

This increasing interest in sustainable use of soil and water in olive cultivation aligns with key policy frameworks such as the Sustainable Development Goals (SDG) of the United Nations for 2030 (European Commission 2015) and the European Union Soil Strategy, which aims to lead the transition toward healthy soils by 2030 (European Commission 2023). Given the extensive area of olive farming in many Mediterranean countries, this trend toward more sustainable olive cultivation systems could significantly contribute to achieving these policy goals. Decades of research on more sustainable olive cultivation systems need to be adapted to specific farming conditions to be successful (e.g., de Ruíz Castroviejo 1969; Gómez-Muñoz et al. 2016).

Within this context, regenerative agriculture has gained attention as a means to enhance sustainability across agricultural systems (Newton et al. 2020). Although there is no single definition of regenerative agriculture, it is broadly understood as an approach that uses soil conservation as a basis for regenerating and improving different ecosystem services, while also delivering social and economic benefits for sustainable food production (Schreefel et al. 2020). Many experts highlight livestock integration as a key component, though consensus is lacking (Newton et al. 2020). Regenerative agriculture therefore focuses on restoring soil quality to improve the provision of ecosystem services (Rhodes 2017), while minimising or eliminating the use of agrochemicals. In olive-growing systems, these principles could contribute to long-term sustainability by mitigating soil degradation, enhancing carbon sequestration and supporting rural livelihoods in marginal areas.

Despite this growing interest in regenerative agriculture, few experimental studies have been conducted on Mediterranean woody crops (Musto et al. 2023). For instance, Fenster et al. (2021) evaluated soil health, biodiversity, yield and profitability in regenerative and conventional almond systems in California. There are multiple studies addressing individual practices relevant to regenerative agriculture in olive systems, such as temporary cover crops that reduce erosion and enhance soil quality (e.g., Gómez, Álvarez, and Soriano 2009; Zuazo et al. 2009) or practices that increase soil organic carbon (Aguilera et al. 2013; Morugán-Coronado et al. 2020; Vicente-Vicente et al. 2016). However, to our knowledge, no study has yet provided an in-depth experimental assessment of the combined impact of regenerative practices in olive orchards.

Thus, significant knowledge gaps remain regarding the comprehensive experimental evaluation of regenerative management in Mediterranean olive systems. Most existing studies address isolated practices without integrating their combined effects or considering diverse edaphoclimatic and socioeconomic contexts. Moreover, evidence remains scarce to support sustainability certifications for regenerative practices, particularly in low-productivity mountainous regions.

This study addresses these gaps by experimentally evaluating the effects of integrated regenerative practices on soil properties and tree nutritional status in a mountainous commercial olive grove in southern Spain. In addition, it assesses how regenerative management influences the provision of ecosystem services and the economic performance of olive production systems.

By providing empirical data under real commercial and marginal growing conditions, this work aims to inform both the scientific community and sustainability certification schemes, contributing to the broader understanding of regenerative agriculture's potential in traditional Mediterranean systems. The specific objectives are:

1. To characterise and compare soil properties and tree nutritional status among an olive grove under regenerative management, a conventionally managed grove and a nearby natural reference site (forest).

2. To assess differences in ecosystem service provision and economic performance between regenerative and conventional management.

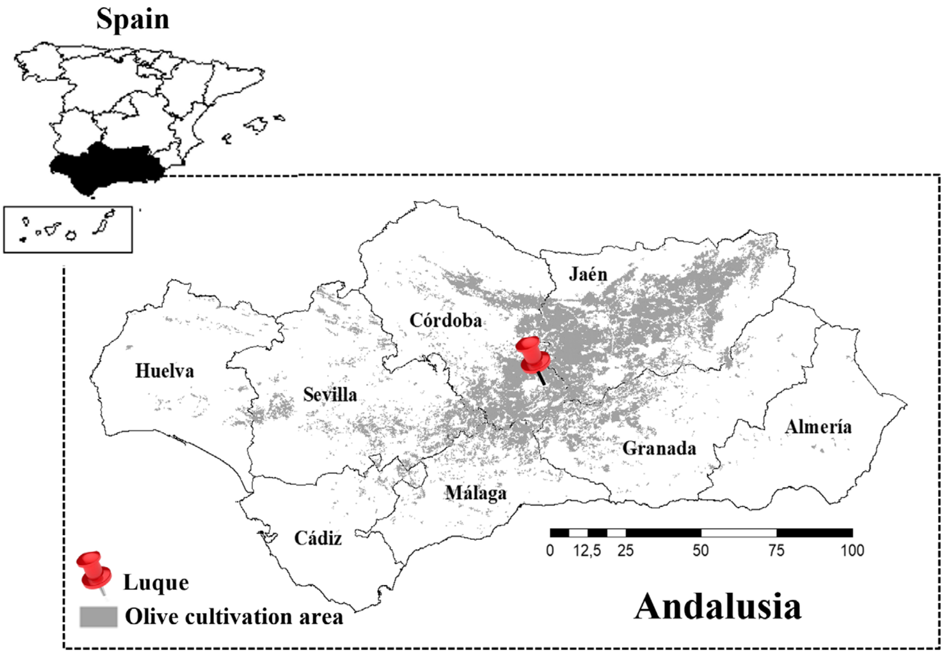

FIGURE 1 | Location map of the study area.

3. To explore the variability of soil properties between two contrasting zones within the same regeneratively managed olive grove.

2 | Materials and Methods

2.1 | Study Sites and Experimental Design

The study area is located in the southern part of the province of Córdoba, in the municipality of Luque (37°33′28.7″ N 4°16.784′ W), in Southern Spain (Figure 1). All the sites are within the Sierras Subbeticas Natural Park in a valley with altitudes between 700 and 900 m. The climate of the area is Mediterranean, characterised by hot, dry summers and cold, rainy winters. The average annual temperature and rainfall in the area are 16.1°C and 613 mm, respectively.

Four study sites were selected, three of which are located in the Valle del Conde regenerative farm. This is a 230 ha farm, of which 217 ha are cultivated with organic olives and the rest are wooded pasture land. The age of the olive trees is around 110–120 years, of *Picudo* and *Picual* varieties. The average slope is 20%, with areas reaching 40%. The plant density ranges between 51 and 100 trees/ha depending on the area within the farm (denser in the less sloping areas). The average annual olive production is 2200 kg/ha. The predominant soils are calcareous cambisols and regosols with lithosols, calcareous fluvisols and cambisols (FAO 2006) and the soil pH is neutral/alkaline and the average carbonate content is 38%.

The soil management of this farm is based on regenerative agriculture practices, including: no tillage allowing a cover crop of adventitious herbaceous vegetation managed through low density sheep grazing, manure application and spreading of chopped olive leaves and pruning residues crushed on the soil surface. Sheep grazing was carried out rotationally in the 217 ha of the olive groves, using contiguous enclosures, of 4 ha each, in which approximately 500 sheep are housed. These animals remain in each enclosure for an average period of 3–4 days before being moved to the next. Occasionally, the duration of grazing in each enclosure can be modified for a few days depending on the amount of vegetation and the reproductive state of the animals.

Regenerative management practices were introduced in this farm in 2019 (6 years prior to the study), replacing conventional management. In the 2023–2024 period, foliar treatments were applied as needed, based on observed deficiencies and included inputs derived from on-farm resources such as potassium soap, magnesium gluconate, potassium humate, free amino acids derived from sheep wool and polysulfide to enhance nutrient absorption, stress resilience and protein synthesis.

Key innovations relative to the previous conventional management included total soil cover, targeted grazing with approximately 2500 sheep, manure incorporation and surface distribution of olive pruning residues perpendicular to the slope. Before adopting regenerative practices, the management was similar to the conventional site, with vegetation cover only in the inter-row, herbicide application under canopy and mechanical clearing of dried vegetation to facilitate harvesting.

Within this farm, two sites in two different plots were selected. One site was representative of most of the farm, showing good ground cover during winter and fall by the cover adventitious vegetation, hereafter called RegG. The other site was representative of some spots in the farm showing a lower cover of vegetation with some bare soil gaps, RegB.

A third site was a small island forest within the farm, hereafter Forest, selected as a benchmark. The forest is characterised by

FIGURE 2 | Views of the selected study sites. RegG and RegB refer to sites in the regenerative olive grove, with good and bad ground cover vegetation respectively; Conv refers to the conventional olive grove; and Forest refers to the natural benchmark site.

the presence of typical Mediterranean woodland species, such as mastic trees (*Pistacia lentiscus*), holm oaks (*Quercus ilex*), terebinths (*Pistacia terebinthus*) and wild olives (*Olea europaea* var. *sylvestris*) and it was selected due to its close proximity (within the same landscape unit), similarity in soil type (predominantly calcareous cambisols) and status as a relatively undisturbed remnant of natural Mediterranean vegetation, thus offering a useful ecological reference for soil condition under minimal human disturbance.

An additional fourth site was selected in a conventional olive farm adjacent to the Valle del Conde farm, with an annual olive production of 2500 kg/ha. This farm, hereafter called Conv, has a soil management based on the control of vegetation cover using herbicides. Specifically, in the 2023–2024 period, pruning was conducted biennially during February and March, with light pruning residues crushed and deposited in the inter-row, perpendicular to the slope. In April, copper-based fungicides (copper oxychloride 38% and copper sulfate 20%) and insecticides (lambda-cyhalothrin 1.5%) were applied. No tillage was performed; instead, the cover vegetation was eliminated under canopy using herbicides (glyphosate 36%). In March and April, nutrient formulations were applied to support fruit set, including amino acids (10.3%), NPK fertilisers (25-5-10) and potassium-rich solutions (11-5-38). In October, a second herbicide application (flazasulfuron 25% and glyphosate 36%) was carried out along with another fungicide treatment (copper oxychloride 50%) and foliar products including 20-10-10 NPK and amino acids (12%). Soil fertilisation was completed in September–October with a 15-15-15 NPK formulation.

Figure 2 provides an image of these four sites at the time of sampling.

2.2 | Soil Sampling and Analysis

The field sampling was carried out at the end of February 2024. At each of the three olive sites, an area of approximately 40 × 40 m considered representative was selected and within that area 18 sampling points were randomly selected, nine in the area under the olive canopy projection and nine at the olive tree inter-row. At each sampled point, one soil sample for analytical determinations was taken for the 0–15 cm soil depth. Additionally, 10 samples for determination of bulk density at 0–5 cm depth using a standard core sampler (98.2 cm^3) in the same area, of which five were under the canopy and five in the inter-row. In the benchmark Forest site, nine samples were taken for soil analytical determinations, also at 0–15 cm depth, taking also five samples for determination of bulk density at 0–5 cm depth. In this study, soil sampling and analysis were restricted to the topsoil layer, as this horizon typically exhibits the most pronounced and rapid changes in response to regenerative management during the initial years of implementation. This depth is particularly sensitive to surface-level interventions such as organic matter additions, grazing and vegetation cover, which are central to regenerative practices (Franzluebbers 2002; Lal 2004; Tautges et al. 2019).

Once in the laboratory, the nine samples taken for analytical determination at each site and location in relation to the tree (below canopy or inter-row) were mixed to obtain a composite sample. The nine samples taken in the Forest area were also mixed to obtain a composite sample. Afterward, these composite samples were air-dried and passed through a 2 mm sieve and subsamples were obtained for the physical, chemical and biological analyses indicated in Table 1. These subsamples were stored refrigerated at 5°C until they were analysed for biological, physical and chemical properties. All physical-chemical

TABLE 1 | Methods of the physical, chemical and biological determinations used.

Parameters	*n*	Method
Physical parameters		
Clay (%)	4	Bouyoucos and Mick (1940)
Sand (%)	4	
Silt (%)	4	
WSA (%)	4	Barthès and Roose (2002)
Bulk density (g/cm^3)	5	Cylindrical core sampler
Soil water content at saturation and field capacity[a] (%)	4	Colman (1947)
Permanent wilting point (%)	4	Saxton and Rawls (2006)
Chemical parameters		
OM (%)	4	Walkley-Black (Stevenson 1982)
Kjeldahl Nitrogen (% w/w)	4	Kjeldahl (Stevenson 1982)
Extractable P (mg/kg)	4	Olsen (Olsen and Sommers 1982)
Extractable K (mg/kg)	4	NH_4Cl (Reeve and Sumner 1971)
Exchangeable Na (mg/kg)	4	
Exchangeable Ca (mg/kg)	4	
Biological parameters		
Bacterial population	6	Plate dilution method (Arias-Giraldo et al. 2021)
Soil microbial functional diversity	6	Biolog EcoPlate system (Garland 1997; Garland and Mills 1991).

Note: n is the number of replications by site and location in relation to the tree (below canopy or inter-row).
[a]Soil cores with soil packed at the same bulk density measured at the field.

analyses were performed using standardised procedures (Table 1). Cations (Ca^{2+}, K^+ and Na^+) were extracted from the soil using an NH_4Cl solution (Reeve and Sumner 1971). The extracted solution was then analysed by flame atomic absorption spectrometry. Regarding OM (%), the oxidizable organic carbon content was multiplied by the Waksman factor to determine the total organic matter (León and Aguilar 1987). Cation exchange capacity (CEC) was estimated from the sum of exchangeable bases extracted with NH_4Cl, taking into account soil pH, clay content and the presence of active lime, determined following the Drouineau method as standardised in AFNOR NF X31-106 (AFNOR 2002). Given the calcareous nature of the soils, CEC values are interpreted comparatively among sites rather than as absolute measurements.

The functional diversity of the microbial community was measured from soil suspensions obtained as described before (Arias-Giraldo et al. 2021) using the Biolog EcoPlate system (Biolog Inc., Hayward, CA, USA). Briefly, absorbance readings were taken with a fluorospectrometer at 590 nm (OD590) every 12 h for 7 days. The average well colour development (AWCD) of each plate was calculated as the mean of the absorbance values for the 31 response wells per reading time after subtracting the OD595 of the control well.

Metabolic diversity of the bacterial communities was assessed by comparing the Community Level Physiological Profiles (CLPP) from all replicates at the end of the incubation period. To account for potential differences in inoculum densities among plates, individual well response was normalised by dividing by the AWCD of the corresponding microtiter plate prior to statistical analysis (Arias-Giraldo et al. 2021). Microbial metabolic functional diversity was calculated using the Shannon diversity index (H′) and substrate richness (R) was determined as the number of carbon substrates metabolised by the soil microbial community (Grzadziel et al. 2018).

Additionally, the number of culturable microorganisms was estimated by the dilution plating technique, counting the number of colony forming units (CFU) developed on R2A agar medium after 4 days of incubation at 25°C.

2.3 | Leaf Sampling and Nutrient Content Analysis

Leaf samples for foliar analysis were carried out in July 2024. For that, composite samples of 100 leaves of the *Picudo* olive variety were taken from three random olive trees in each study site (RegG, RegB and Conv) following standard procedures (Fernández-Escobar et al. 1999), as this variety represented approximately 80% of the plantation. The leaves were analysed for nutrient content following standardised techniques (Fernández-Escobar et al. 1999) in a homologated laboratory.

2.4 | Evaluation of Ecosystem and Economic Services

Ecosystem services were classified into provisioning, regulating, supporting and cultural categories following the framework proposed by the Millennium Ecosystem Assessment (MEA 2005), which provides a widely accepted conceptual structure for organising ecosystem services in agroecosystems. The specific ecosystem services considered within each category were selected according to their relevance to Mediterranean olive grove systems and the ecosystem functions and benefits typically associated with olive cultivation. This selection was based on the ecological and agronomic effects commonly linked to olive grove management practices, as described in the literature for perennial and agricultural systems (de Groot et al. 2010; Power 2010) and on the measured soil, biological and agronomic indicators obtained in this study. The selected ecosystem services and their qualitative classification are summarised in Table 2.

The ecosystem service assessment followed an author-defined qualitative–semi-quantitative scoring approach designed to

TABLE 2 | Comparative evaluation of ecosystem and economic service levels under regenerative and conventional management systems.

Service type	Ecosystem service	Management system		Reason
		Conventional	Regenerative	
Provisioning	Olive and olive oil production	Medium	Medium	Olive groves managed under regenerative or multifunctional systems generally show medium productivity levels compared to irrigated or high-intensity regimes, which achieve higher yields due to greater water inputs and planting densities. However, farmers managing regenerative olive groves (with ground cover or controlled grazing) often report no yield reduction under dry Mediterranean conditions, particularly in mountainous areas where improvements in soil health compensate for lower input use.
	Biomass and firewood	Medium	Medium	Medium, since they vegetative growth is in the medium range as it is the yield.
	Pollinators and secondary products (honey, aromatic plants)	Low	High	Regenerative agriculture allows vegetation growth with flowering plants. We support this from field observations.
Regulation	Carbon sequestration and climate regulation	Medium	High	Regenerative practices increases SOCS as compared to a soil management based on the control of vegetation cover using herbicides or poor vegetation cover (RegG, 7.5 Mg ha^{-1}; RegB 5.1 Mg ha^{-1}; Conv, 5.3 Mg ha^{-1}).
	Water regulation (infiltration and retention)	Medium	High	Regenerative practices increases θ_{FC}, θ_S (%) and θ_{PWP}, particularly in RegG (40.7%, 48.7%, 24.2%, respectively) compared to Conv (30%, 37.9%, 19.5%). (These values correspond to the averages of measurents taken under the canopy and in the inter-row áreas).
	Erosion control	Low	High	Regenerative agriculture enhances ground cover and soil aggregate stability, thereby reducing erosion. WSA were higher in RegG and RegB (62.3% and 62.6%, respectively) compared to the Conv site (45.3%). Furthermore, cover crops are a key factor in mitigating soil erosion, while also enhancing water infiltration and availability (Sastre et al. 2016).
	Biological pest control	Low	Medium	Regenerative agriculture enhances natural pest control by increasing biodiversity and fostering a more complex ecological network. The presence of ground cover, hedgerows and grazing provides habitats for natural enemies, including predatory insects and birds, thereby reducing the likelihood of pest and disease outbreaks compared to conventional systems. In addition, maintaining cover crops benefits ant communities and further contributes to pest regulation in olive groves (Martínez-Núñez et al. 2021).
	Soil quality	Medium	High	Regenerative agriculture enhances key soil quality indicators like; OM, WSA and θ_{FC}. For instance, The RegG site exhibited the highest OM concentration, averaging 7.3%, compared to 4.7% at the Conv site.

(Continues)

TABLE 2 | (Continued)

		Management system		
Service type	**Ecosystem service**	**Conventional**	**Regenerative**	**Reason**
Supporting	Soil fertility	Medium	Medium	Regenerative agriculture increases nutrient cycling and certain nutrient contents. This is supported by our measurents, which showed that soil macronutrient concentrations (N, P and K), followed a tren similar to that observed for OM concentration.
	Pollination	Low	High	Regenerative agriculture enhances pollination services in olive groves by promoting the growth of flowering vegetation, which provides abundant and temporally extended nectar and pollen resources. The maintenance of ground cover, hedgerows, and flowering plants also creates microhabitats and refuges for pollinators such as wild bees, wasps, and butterflies, supporting a more diverse and stable pollinator community. In addition, practices such as no-tillage and the avoidance of herbicides reduce habitat disturbance and chemical exposure, further benefiting pollinator abundance and efficiency (Villa et al. 2021; Dellapiana et al. 2025; Moreno-Delafuente et al. 2022).
	Nutrient cycling	Medium	Medium	In regenerative agriculture, incorporating pruning residues and applying composted manure or olive pomace enhances carbon and nitrogen dynamics, increases soil organic matter and nutrient content (C, N, P), and can even improve fruit oil content over time (Gómez-Muñoz et al. 2016; Fernández-Hernández et al. 2015). In conventional systems, these benefits are partially offset by the use of synthetic fertilisers. Therefore, a medium level was assigned to both management systems for nutrient cycling.
Cultural	Landscape and aesthetic value	Medium	High	Regenerative agriculture preserves a diverse and seasonally changing landscape mosaic, reduces erosion, and maintains traditional land features, thereby enhancing aesthetic and cultural values compared to conventional systems. Raz et al. (2024) reported that organic olive groves enhance multifunctionality by integrating economic, ecological, and social values. They also highlighted that maintaining ground vegetation significantly contributes to the groves high ecological and social value.
	Heritage and traditional identity	Medium	High	The presence of sheep in olive groves provides effective management of ground cover, eliminating the need for machinery such as manual or mechanical mowers. This practice contributes to biodiversity, supplies additional organic fertilisation without external inputs, and also aids in controlling olive twig borers (*Prays oleae*) (Torres et al. 2016).
	Well-being and connection with nature	Low	High	Regenerative olive farming enhances farmers' well-being and connection with nature by promoting direct interaction with ecological processes, biodiversity, and traditional land stewardship, whereas conventional systems, driven by mechanisation and input dependence, tend to alienate farmers from natural cycles. Brown et al. (2021) indicate that regenerative agriculture may be associated with higher levels of farmers' well-being, thereby contributing to the long-term sustainability of agricultural systems.

support a comparative analysis between regenerative and conventional management systems. For each ecosystem service, the level of provision was classified as Low, Medium or High, reflecting differences in functionality, stability, resilience and dependence on external inputs. Specifically, Low indicates services that are scarce, weak or highly dependent on external inputs; Medium indicates services that are present but limited in quantity or stability or partially dependent on management; and High indicates services that are fully functional, resilient, stable and ecologically significant. Assigned scores were used directly to express relative differences in ecosystem service provision between management systems and no formal weighting, normalisation or aggregation across ecosystem services was applied.

To facilitate comparison and graphical representation, qualitative scores were translated into numerical values (1 = low, 5 = medium, 10 = high). These values represent relative weights and do not correspond to absolute measurements of ecosystem services, but rather to a comparative, semi-quantitative evaluation. This approach is conceptually consistent with matrix-based ecosystem service assessments commonly used in agroecosystem research (Burkhard et al. 2009; Burkhard et al. 2012), while the specific scoring scale was defined by the authors based on field evidence and system characteristics. Within the supporting and regulating service categories, soil organic carbon stock (SOCS) was quantified as a key indicator of soil quality and system sustainability. SOCS was calculated for both regenerative (RegG and RegB) and conventional management systems using bulk density (g cm^{-3}) at a depth of 12.5 cm. This value was derived from the field-measured bulk density at 0–5 cm, multiplied by a dimensionless coefficient of 1.05 (corresponding to the 5–20 cm layer). The coefficient was derived from the linear relationship between soil depth and the increase in bulk density fraction, as described by Gómez et al. (2022). The calculation was based on bulk density (BD, g cm^{-3}) measured at a depth of 12.5 cm, organic carbon content (C, %) and the sampling depth (D, m) of 0.15 m, according to the following equation: SOCS (Mg ha^{-1}) = BD × C × D × 10. It should be noted that the analysis of the topsoil layer alone does not accurately reflect the carbon sequestration potential of a given management practice, as deeper soil horizons may significantly contribute to the total carbon pool.

In addition, economic indicators were integrated to compare the profitability of the management systems: regenerative and conventional. Olive yield (kg ha^{-1}), selling price (€ kg of olive^{-1}), gross income (€ ha^{-1}), total cost (€ ha^{-1}), net balance income (€ ha^{-1}) and the benefit–cost ratio (B:C) were recorded and calculated. These data allowed the assessment of the economic dimension of sustainability, complementing the ecosystem service evaluation for a comprehensive understanding of system performance. For this purpose, data from the 2022 to 2023 campaign were considered. For conventional management, official data corresponding to traditional mechanizable olive groves were used (AEMO 2023), while for regenerative management, due to the absence of official reports, data from Valle del Conde regenerative farm were employed. Although to ensure comparable conditions, the costs of personnel (qualified worker—tractor driver and pruner: 10.15 €/h; farm labourer: 9.85 €/h) and machinery (tractor: 36.50 €/h; sprayer: 11.50 €/h; shredder: 8.80 €/h) reported by AEMO (2023) were considered. Furthermore, for comparative purposes, the average yield of the regenerative farm (2200 kg ha^{-1}) was assigned to the conventional system, as both systems exhibit similar mean production levels.

The total cost was calculated as the sum of all expenses associated with the management operations carried out in the olive grove. Gross income (€ ha^{-1}) was determined by multiplying olive yield by the selling price. Net balance income (€ ha^{-1}) is defined as the difference between gross income and total cost, while the benefit–cost (B:C) ratio was obtained as the ratio between gross income and total cost.

2.5 | Statistical Analysis

Evaluation of significant differences between the different variables was made using the parametric ANOVA test ($p < 0.05$) after checking that data met the normality, homogeneity of variances, randomness and independence hypotheses. When the assumptions of normality were not met, the non-parametric Kruskal–Wallis test was used. Once the parametric or non-parametric tests were applied, the post hoc multiple comparison Tukey test was applied to compare between means of the different levels and thus identify those groups for which the differences were significant. In those cases where the hypothesis of homogeneity of variances was not met, the Games-Howell method was applied. The software used to perform the different statistical analyses was Statgraphics Centurion 19.

The average area under the curve (AUC) of the AWCD (AUCAWCD) over time was calculated using the trapezoidal integration method. Final absorbance values (OD_{595}) from the Community-Level Physiological Profiling (CLPP) were subjected to unsupervised hierarchical clustering based on Euclidean distance and Ward's linkage method and scaled data were used to generate a heatmap. Differences in substrate metabolization profiles were assessed with a principal component analysis (PCA) followed by a permutational multivariate analysis of variance (PERMANOVA) based on Euclidean distances. Bacterial population data were log-transformed before analysis. All analyses and plots were performed in R, using the vegan, factoextra, pheatmap, pracma and ggplot2 packages.

3 | Results

3.1 | Soil Physical Properties

The soil textural class in the four sampled sites was clayey loam (Soil Survey Division Staff 1993), although there were slight differences in sand, silt and clay among sites (Table 3). Average bulk density values in the olive groves ranged from 1.2 to 1.4 g cm^{-3}, with an average value of 1.0 g/cm^3 in the Forest site, with no significant differences among sites (Table 3). Water-stable aggregates (WSA) differed significantly among sites (Table 3). The Forest site had the highest WSA (82.6%), followed by the regenerative olive sites RegG and RegB (62.3% and 62.6%), which were significantly higher than the conventional site (Conv, 45.3%). Within the regenerative grove, WSA tended to be higher under the canopy, while the opposite pattern was observed in Conv. Gravimetric water content at field capacity (θ_{FC}) and saturation

TABLE 3 | Soil physical properties for the four different sampling sites (mean values followed by ± standard deviation), indicating location in relation to the tree canopy.

		Physical parameters[a]															
Sampling site	**Area**	**Bulk density (g/cm^3)*,****		**Clay (%)****		**Sand (%)**		**Silt (%)****		**WSA (%)**		**θ_{FC} (%)***		**θ_S (%)***		**θ_{PWP} (%)**	
RegG	Under canopy	1.2 ± 0.1 a	A	37.3 ± 1.3 de	B	36.3 ± 0.5 b	B	26.8 ± 1.3 b	B	65.3 ± 3.2 d	B	40.9 ± 0.7 c	B	49.1 ± 0.5 b	B	24.1 ± 0.7 c	B
	Inter-row	1.2 ± 0.1 a		34.8 ± 1.5 cd		37.3 ± 1.0 b		27.8 ± 2.1 b		59.3 ± 6.9 cd		40.5 ± 1.6 c		48.2 ± 2.8 b		24.2 ± 0.5 c	
RegB	Under canopy	1.2 ± 0.1 a	A	48.8 ± 0.5 f	C	30.3 ± 1.5 a	A	21.3 ± 1.5 a	A	78.7 ± 4.2 e	B	34.3 ± 3.1 b	A	42.4 ± 2.8 ab	A	29.6 ± 0.1 d	C
	Inter-row	1.4 ± 0.2 a		39.3 ± 0.5 e		35.8 ± 0.5 b		25.0 ± 0.0 ab		46.5 ± 5.0 ab		26.9 ± 1.9 a		35.2 ± 1.1 a		24.5 ± 0.2 c	
Conv	Under canopy	1.2 ± 0.1 a	A	25.5 ± 1.7 a	A	38.3 ± 1.3 b	B	36.5 ± 1.0 d	C	40.3 ± 2.4 a	A	31.1 ± 1.1 ab	A	40.1 ± 2.2 a	A	17.4 ± 0.9 a	A
	Inter-row	1.4 ± 0.2 a		32.3 ± 1.9 bc		35.5 ± 1.0 b		32.5 ± 2.4 c		50.3 ± 2.1 bc		28.9 ± 2.1 a		35.7 ± 1.3 a		21.5 ± 0.9 b	
Forest	Under canopy	1.0 ± 0.3 a	A	30.3 ± 2.2 b	A	37.5 ± 2.1 b	B	32.8 ± 2.5 cd	C	82.6 ± 2.1 e	C	49.3 ± 2.5 d	C	60.5 ± 2.6 c	C	24.1 ± 0.7 c	B

Note: WAS is water-stable aggregates. θ_{FC} and θ_{WS} are gravimetric water content at field capacity and saturation respectively. RegG and RegB refer to sites in the regenerative olive grove with good and bad ground cover respectively. Conv the conventional olive grove and Forest to the natural benchmark site.

[a]Different upper-case letters indicate significantly statistical differences (at $p < 0.05$) among the four different sampling sites aggregating under canopy and inter-row samples for the same site. Different lower-case letters indicate significantly statistical differences (at $p < 0.05$) among the seven sampling sites when disaggregating by location to the tree.

*Kruskal–Wallis test between areas under canopy and inter-rows.

**Kruskal–Wallis test used between sampling sites (RegG. RegB. Conv and Forest).

(θ_S) were significantly higher in the Forest site (49.3% and 60.9%, respectively) than in the olive groves (Table 3). Among the olive grove sites, RegG presented significantly higher values of θ_{FC} and θ_S, 40.7% and 48.7%, while RegB and Conv had similar values of θ_{FC} and θ_S, approximately 30.3% and 38.4% respectively (Table 3). The permanent wilting point (θ_{PWP}) was highest in RegB (27.1%) and similar in the Forest (24.1%) and RegG (24.2%) sites, while the lowest value was recorded in Conv (19.5%). No significant differences were found between the Forest and the regenerative olive sites, however, significant differences were observed between RegG and RegB. In both RegB and Conv, significant differences in θ_{PWP} were detected between the inter-row and canopy positions, although with contrasting patterns: θ_{PWP} was higher under the canopy in RegB (29.6%), whereas it was lower in Conv (17.4%) (Table 3).

3.2 | Soil Chemical Properties

Soil organic matter (OM) concentration was very high in the Forest site (13.5%), significantly exceeding that in olive groves (Table 4). Among the olive sites, RegG presented the highest OM concentration (average of 7.3%), while RegB and Conv presented similar average values, 4.6% and 4.7% respectively. In the RegG site OM was lower in the area under the canopy, 5.6%, as compared to the inter-row area, 8.6%, while in the RegB OM was higher in the area under the canopy, 5.9%, as compared to the inter-row area, 3.2%. Soil organic N concentration followed a similar pattern, with the highest value in Forest (0.7%), intermediate in RegG (0.4%) and around 0.25% in RegB and Conv. Canopy-inter-row differences mirrored those of OM. Extractable P showed less variation, with no significant differences among Forest, RegG and Conv (32.4–44.8 mg/kg), while RegB had a significantly lower value (13.6 mg/kg). Higher P concentrations were found under the canopy in RegG and Conv. Extractable K was highest in the Forest (1159.8 mg/kg), lowest in Conv (475.25 mg/kg) and intermediate in RegG and RegB (694 mg/kg). In all olive sites, K was consistently higher under the canopy (Table 4). Estimated cation exchange capacity (CEC) and soil electrical conductivity (EC) presented a trend similar to that observed for extractable K, with highest and significant values in the Forest site, lowest in Conv and intermediate (and similar) in the RegG and RegB sites (Table 4). Na concentrations did not differ significantly among sites and showed no clear canopy versus inter-row pattern (Table 4). Soil Ca was high across all sites, highest in Forest (6435.3 mg/kg), lowest in Conv (4284.3 mg/kg) and intermediate in RegG and RegB (5393.3 and 4948.1 mg/kg).

3.3 | Soil Biological Properties

A significantly lower overall soil metabolic activity was observed in the Conv site (144.7) compared to the regenerative grove; RegG and RegB (175.3 and 184.7, respectively) and forest (195.8) sites, as indicated by lower AUCAWCD values (Figure 3A). Furthermore, no significant differences were found between the AUCAWCD values of soils from regenerative treatments (RegG and RegB), suggesting similar overall microbial activity between them. In parallel, the number of culturable bacteria (Figure 3B) did not differ significantly among the Forest, RegG and RegB sites, with an average value of 5.8 log (CFU/g of soil). The Conv site presented a significantly lower population level of 5.3 log (CFU/g of soil). There were significant differences in culturable bacterial populations between the under canopy and inter-row areas only in RegB. Microbial functional diversity (Shannon index, H′) followed a similar pattern: Forest (3.4), RegG (3.4) and RegB (3.3) had comparable values, all significantly higher than Conv (3.2). We did not observe differences in H′ in the olive sites, except for RegB, where H′ was higher under the canopy as compared to the inter-row areas (Figure 3C). Richness followed a pattern similar to that observed in the two previously analysed biological indices, with no significant differences among the Forest (29.5), RegG (29.5) and RegB (28.3). The lowest value was recorded in the Conv site, with 25.9, which differed from the regenerative olive orchards, where no significant differences in richness were observed. The heatmap (Figure 4) revealed distinct metabolic profiles across the sites, demonstrating that soil management practices significantly influenced carbon substrate utilisation. The seven treatments were grouped into two main clusters. Notably, treatments under conventional (Conv) management (both inter-row and under-canopy) and RegB inter-row clustered together, while all other regenerative treatments, including RegG (both inter-row and under-canopy), RegB under-canopy and forest soil, formed a separate cluster. Principal component analysis (PCA) of carbon source metabolization also revealed distinct clustering patterns among treatment groups. The first two principal components accounted for 28.7% and 12.1% of the total variability, respectively. PERMANOVA analysis showed significant differences in compound utilisation profiles among treatments ($F = 4.22$, $R^2 = 0.42$, $p = 0.001$) (Figure 5).

3.4 | Leaf Nutrient Content

Leaf macronutrient concentrations, N, K, Ca and Mg, did not differ significantly among the three sampled olive sites (except for P, 0.11%) with average values of 1.40%, 1.11%, 1.00% and 0.14% respectively (Table 5). On the other hand, the sites in the regenerative olive grove, RegG and RegB, had significantly higher Fe, Mn, Cu, Zn and B concentrations (86.4, 33.7, 321.8, 23.7 and 47.0 mg/kg respectively) as compared to the Conv site (64.3, 21.5, 84.7, 12.7 and 26.1 mg/kg respectively).

3.5 | Economic Evaluation Between Regenerative and Conventional Management

The comparative analysis of regenerative and conventional olive grove management systems highlights substantial differences in their economic performance. Gross income under regenerative management reached 2824.99 € ha^{-1}, surpassing that of the conventional system (2427.86 € ha^{-1}). Moreover, total production costs were lower in the regenerative system (1485.28 € ha^{-1}) compared to the conventional system (1733.23 € ha^{-1}), resulting in a significantly higher net income for the regenerative farm (1339.72 € ha^{-1}) relative to the conventional one (466.77 € ha^{-1}). Consequently, the benefit–cost ratio (B:C) also differed markedly between the two systems, with values of 1.90 for regenerative management and 1.40 for conventional management (Table 6).

TABLE 4 | Soil chemical physical properties for the four different sampling sites (mean values followed by ± standard deviation), indicating location in relation to the tree canopy.

Sampling site	Area	Chemical parameters[a]															
		O.M. (%)*		N (%)		P (mg/kg)*,**		K (mg/kg)*		CEC (meq/100 g)*,**		Na (mg/kg)*,**		Ca (mg/kg)*,**		EC (mS/cm)*	
RegG	Under canopy	5.9 ± 0.4 bc	B	0.3 ± 0.0 c	B	47.0 ± 16.9 abc	B	833.0 ± 17.9 c	B	32.0 ± 1.4 bc	B	42.0 ± 4.2 ab	A	5086.8 ± 314.3 bcd	B	0.3 ± 0.0 a	B
	Inter-row	8.6 ± 0.7 d		0.5 ± 0.0 d		36.8 ± 1.3 b		613.0 ± 17.8 b		34.8 ± 1.3 cd		44.3 ± 2.4 b		5699.8 ± 125.5 d		0.4 ± 0.1 ab	
RegB	Under canopy	5.9 ± 0.0 c	A	0.3 ± 0.0 c	A	15.8 ± 5.9 a	A	912.8 ± 45.9 c	B	36.8 ± 0.5 d	B	47.8 ± 2.1 b	A	5601.3 ± 136.7 d	C	0.3 ± 0.0 a	AB
	Inter-row	3.2 ± 0.2 a		0.2 ± 0.0 a		11.3 ± 2.6 a		417.3 ± 17.8 a		29.0 ± 0.0 b		63.3 ± 22.6 ab		4294.8 ± 34.4 b		0.3 ± 0.0 a	
Conv	Under canopy	3.8 ± 0.2 a	A	0.2 ± 0.0 b	A	59.8 ± 5 c	B	601.0 ± 4.2 b	A	24.8 ± 0.5 a	A	37.5 ± 1.9 a	A	3755.3 ± 146.8 a	A	0.3 ± 0.0 a	A
	Inter-row	5.5 ± 0.1 b		0.2 ± 0.0 b		23.8 ± 11.6 ab		349.5 ± 31.3 a		29.5 ± 0.6 b		42.5 ± 8.1 ab		4813.3 ± 65.1 c		0.2 ± 0.1 a	
Forest	Reference	13.5 ± 0.5 e	C	0.7 ± 0.0 e	C	44.8 ± 6.9 bc	B	1159.8 ± 62.5 d	C	42.0 ± 1.2 e	C	124.5 ± 84.1 ab	A	6435.3 ± 91.4 e	D	0.5 ± 0.0 b	C

Note: OM is organic matter, CEC is cation exchange capacity, and EC is soil electrical conductivity. RegG and RegB refer to sites in the regenerative olive grove, with good and bad ground cover respectively, Conv the conventional olive grove, and Forest to the natural benchmark site.
[a]Different upper-case letters indicate significantly statistical differences (at $p < 0.05$) among the four different sampling sites aggregating under canopy and inter-row samples for the same site. Different lower-case letters indicate significantly statistical differences (at $p < 0.05$) among the seven sampling sites when disaggregating by location to the tree.
*Kruskal–Wallis test between areas under canopy and inter-rows.
**Kruskal–Wallis test used between sampling sites (RegG, RegB, Conv and Forest).

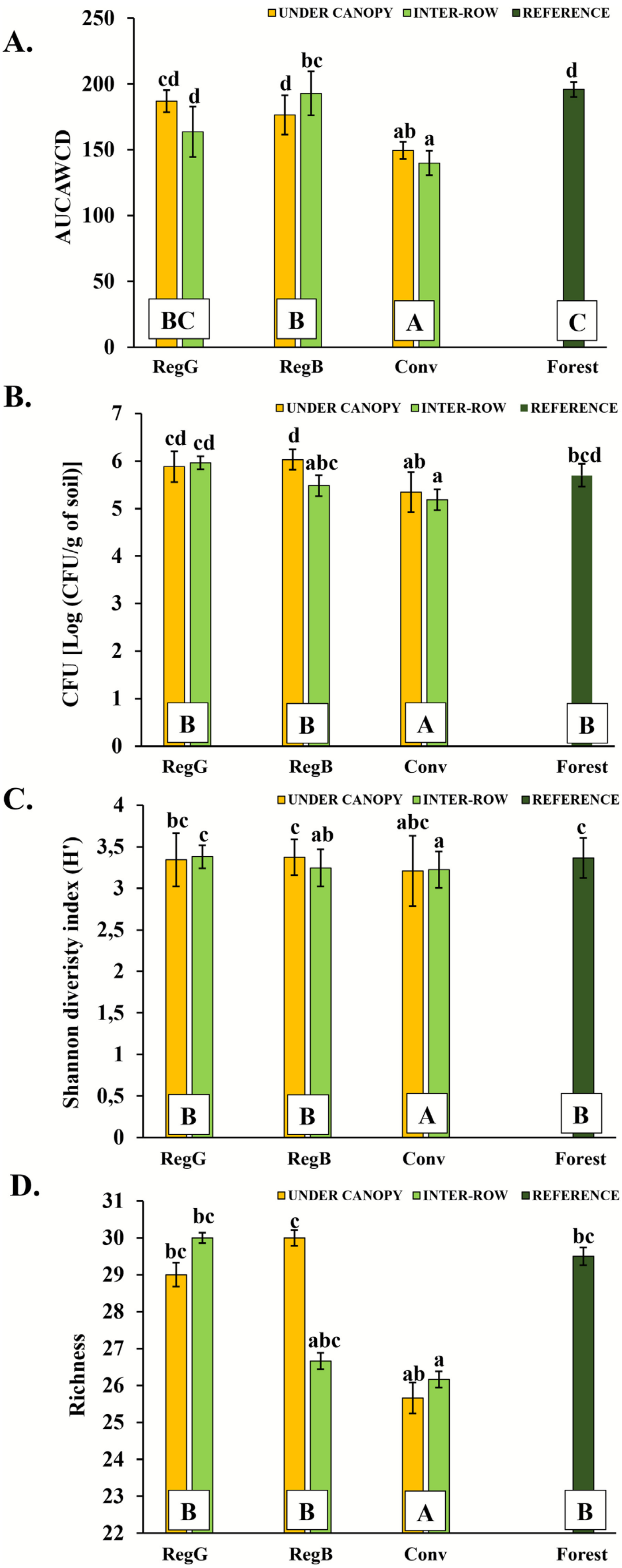

FIGURE 3 | Legend on next page.

FIGURE 3 | (A) Average area under the curve (AUC)* of the average well colour development (AWCD) over time from the Biolog EcoPlateTM analysis. (B) Number of culturable bacterial population as measured by the number of colony forming units Log(CFU/g of soil). (C) Shannon diversity index (H′)*. (D) Substrate richness (R)*. Bars indicate mean values and the error bars the standard deviation. RegG and RegB refer to sites in the regenerative olive grove, with good and bad ground cover respectively, Conv the conventional olive grove and Forest to the natural benchmark site. Different upper-case letters indicates significantly statistical differences ($p < 0.05$) among the four different sampling sites aggregating under canopy and inter-row samples for the same site. Different lower-case letters indicates significantly statistical differences ($p < 0.05$) among the seven sampling sites when disaggregating by location to the tree. *Kruskal–Wallis test.

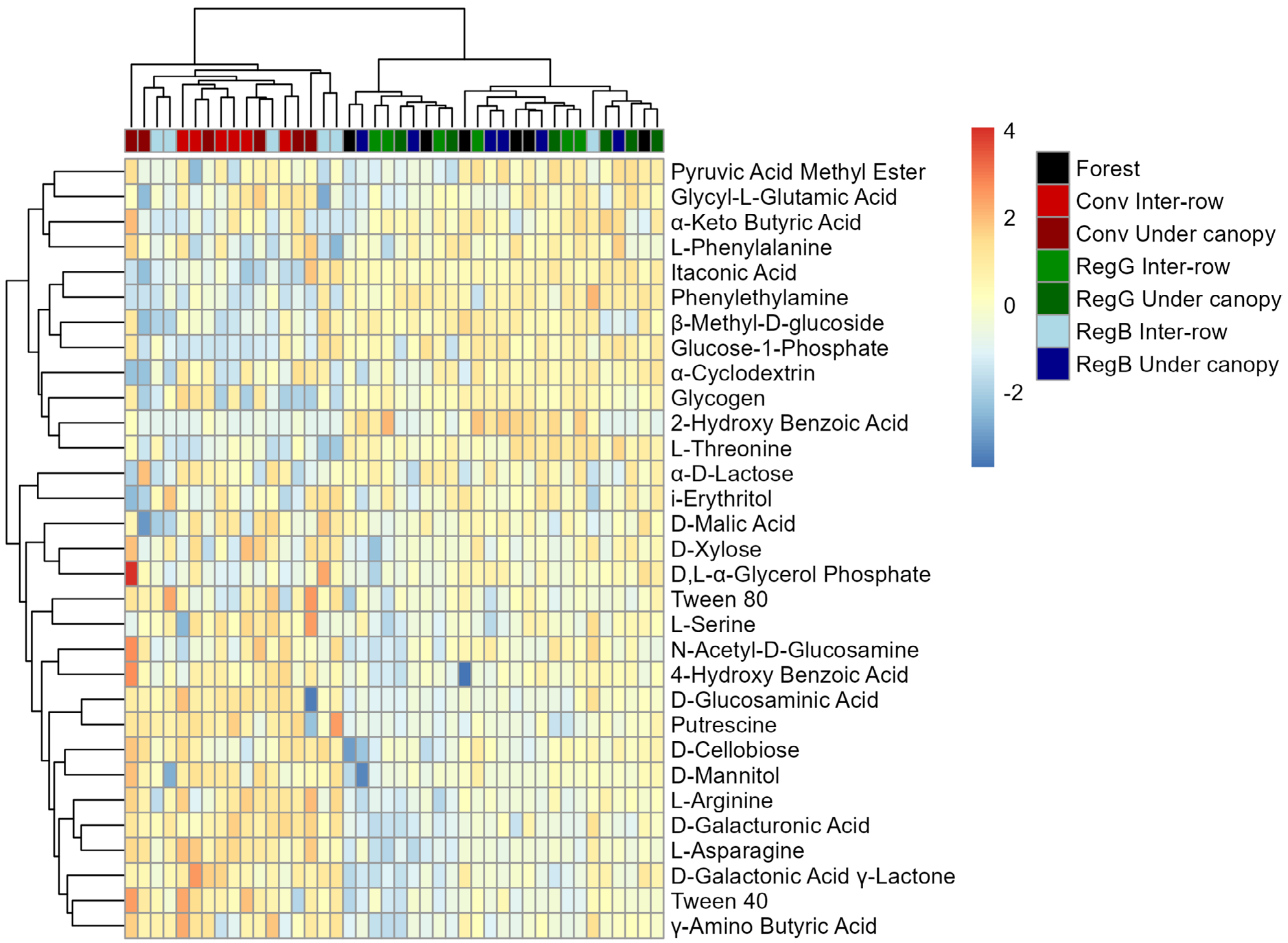

FIGURE 4 | Heatmap and hierarchical clustering using Ward's method and Euclidean distance applied to the 31 carbon sources and treatment groups to identify similarities in substrate utilisation. Each row represents a substrate and each column corresponds to a replicate of a treatment. Colour intensity reflects absorbance values, with higher values indicating greater metabolization of the respective carbon sources.

A detailed examination of cultivation operations indicates that the regenerative system considerably reduces expenditures associated with soil maintenance (98.50 € ha^{-1} vs. 433.51 € ha^{-1}), pest and disease control (140.20 € ha^{-1} vs. 251.81 € ha^{-1}), sucker removal (29.55 € ha^{-1} vs. 63.28 € ha^{-1}) and fertilisation (160.99 € ha^{-1} vs. 248.65 € ha^{-1}) when compared to conventional management. Harvesting costs, however, were slightly higher in the regenerative system due to the orography and slope of the terrain (Table 6).

3.6 | Ecosystem Services Evaluation

The comparative assessment of ecosystem services between conventional and regenerative management systems revealed consistent differences across all service categories (Figure 6). Regenerative management exhibited higher overall scores in every service type, totaling 20, 45, 20 and 30 points for provisioning, regulating, supporting and cultural services, respectively, whereas the conventional system obtained 11, 17, 11 and 11 points.

Within the provisioning services, both management systems showed similar scores for olive and olive oil production and biomass and firewood (score = 5), indicating that the adoption of regenerative practices does not negatively affect productive yield. However, a pronounced difference was observed in pollinators and secondary products (score = 10 in regenerative vs. 1 in conventional), contributing to the higher total provisioning

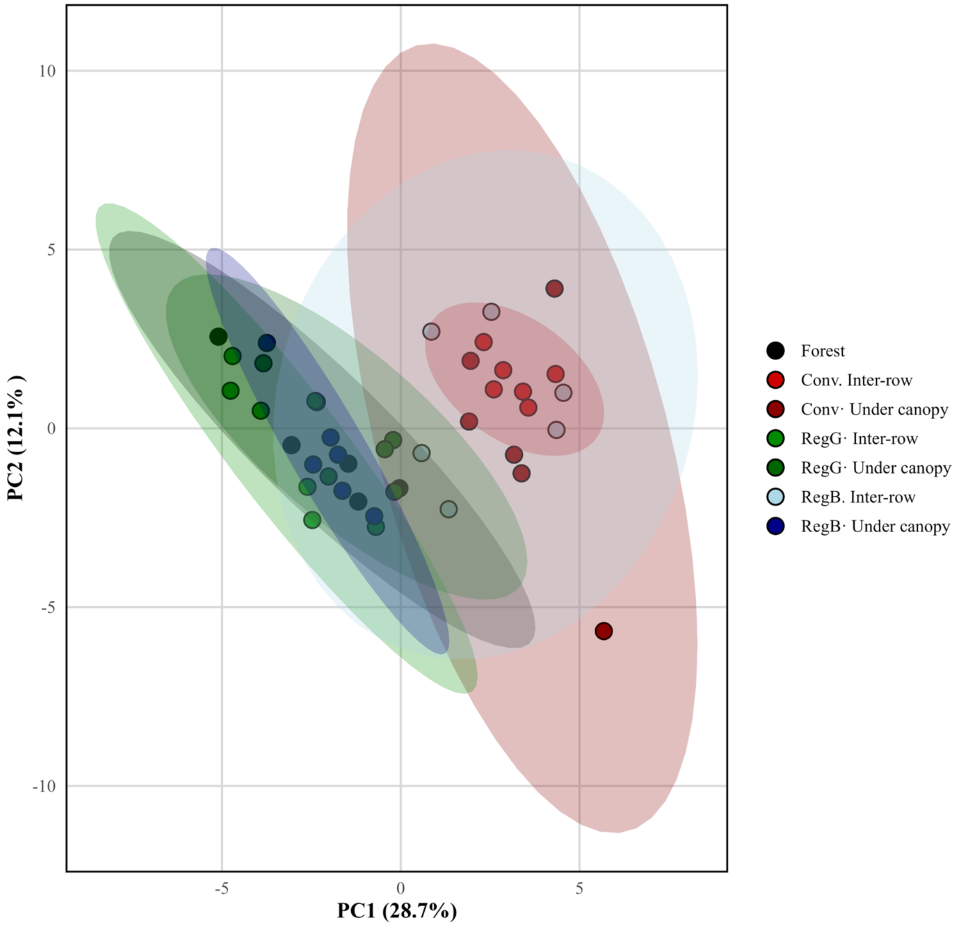

FIGURE 5 | Principal Component Analysis (PCA) of compound profiles. Each point represents an individual sample coloured according to treatment group. Shaded ellipses indicate the 95% confidence interval for each treatment.

value under regenerative management. The regulating services displayed the largest contrast between systems. Regenerative management reached the maximum level (10) in all subcategories (carbon sequestration and climate regulation, water regulation, erosion control, biological pest control and soil quality), accumulating a total of 45 points, compared to 17 in the conventional system. These results highlight the positive influence of regenerative practices on soil structure, water retention and biotic regulation processes. In the supporting category, both systems maintained similar intermediate values for soil fertility (score = 5), while regenerative management scored higher in pollination and nutrient cycling (10 vs. 1–5). The total supporting service score was 20 for the regenerative system and 11 for the conventional one, reflecting enhanced ecosystem functionality under regenerative management. Finally, cultural services presented the most significant relative difference. Regenerative management achieved the maximum score (10) in landscape and aesthetic value, heritage and traditional identity and well-being and connection with nature, resulting in a total of 30 points, nearly tripling the conventional system's score (11). Overall, regenerative management provided superior performance in nearly all ecosystem service categories, especially in regulating and cultural dimensions, while maintaining equivalent provisioning capacity compared to the conventional approach.

Within the supporting and regulating service categories, the soil organic carbon stock (SOCS) differed significantly under RegG (7.9 Mg ha^{-1}), where the vegetation cover was well developed and dominated by adventitious species that provided good ground coverage. In contrast, RegB (5.3 Mg ha^{-1}) exhibited a lower vegetation cover with some bare soil patches, while Conv (5.6 Mg ha^{-1}) showed opposite characteristics. No significant differences were found between the latter two management systems (Table 7).

4 | Discussion

4.1 | Soil Physical Properties

The soil physical properties evaluated in the three olive orchard sites presented values within the typical range (e.g., Gómez, Sobrinho, et al. 2009; Soriano et al. 2012) and were considered adequate indicators of soil quality. The average bulk density of the topsoil measured in olive groves, 1.1–1.2 g/cm^3, were not statistically different from the undisturbed Forest site, 1.0 g/cm^3. This suggests that controlled traffic helped minimise differences between under-canopy and inter-row areas within the regenerative groves. While some studies report lower bulk density under canopy due to reduced compaction (e.g., Gómez et al. 2022), such contrasts were not evident here, likely due to moderate compaction across areas. In the Conv site, soil fertilisation may explain the lack of differences between canopy zones. Soil aggregate stability in water (WSA) is one of the most

TABLE 5 | Nutrient concentration in leaves in the different study areas (RegG, RegB and Conv) for the *Picudo* variety (mean values ± standard deviation).

Sampling site	Leaf nutrient concentration[a]									
	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (mg/kg)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	B (mg/kg)
RegG	1.38 ± 0.1 a	0.10 ± 0.0 a	1.11 ± 0.2 a	0.98 ± 0.1 a	0.15 ± 0.0 a	82.43 ± 1.1 b	35.40 ± 2.5 b	360.57 ± 31.7 c	25.93 ± 1.0 c	47.37 ± 6.6 b
RegB	1.45 ± 0.1 a	0.10 ± 0.0 a	1.12 ± 0.2 a	0.86 ± 0.1 a	0.12 ± 0.0 a	90.43 ± 2.8 c	31.93 ± 3.7 b	282.97 ± 22.0 b	21.50 ± 0.7 b	46.53 ± 2.0 b
Conv	1.37 ± 0.2 a	0.12 ± 0.0 b	1.10 ± 0.0 a	1.15 ± 0.2 a	0.14 ± 0.0 a	64.30 ± 3.3 a	21.47 ± 0.3 a	84.67 ± 24.7 a	12.70 ± 1.6 a	26.07 ± 1.6 a

[a]Different lower-case letters indicate significantly statistical differences (at $p < 0.05$) among the three sampling sites. RegG and RegB refer to sites in the regenerative olive grove, with good and bad ground cover respectively, Conv the conventional olive grove. One-way ANOVA test.

accepted indicators of an adequate soil structure and good soil quality (Six, Elliott, and Paustian 2000) and is regularly used in olive grove studies (e.g., Gómez, Álvarez, and Soriano 2009; Cañasveras et al. 2009). Our results show a very high WSA stability in the Forest site (above 80%), as expected, in the very upper range of WSA values (Barthès and Roose 2002). Regenerative sites also exhibited high WSA values (~60% for both RegG and RegB), likely reflecting higher soil organic matter (OM) content and low compaction. These values were significantly higher (~50% increase) than those observed in the Conv site (~45%), which although they were lower, still exceeded the minimum threshold for adequate structure (Barthès and Roose 2002). Although RegB and Conv presented similar levels of soil organic matter, higher aggregate stability in RegB may result from other factors associated with regenerative management. The presence of continuous ground cover likely promotes greater root growth and rhizosphere activity, leading to increased microbial biomass and production of binding agents such as polysaccharides and fungal hyphae (Gentsch et al. 2024; Li et al. 2024), which enhance aggregate formation and persistence. Thus, the improvement in WSA in RegB suggests that biological and structural processes linked to regenerative management can strengthen soil aggregation independently of organic matter content alone (Yan and Arthur 2025). Unlike findings in more intensively managed groves (e.g., Gómez, Sobrinho, et al. 2009), no differences in WSA were found between canopy zones in our sites, likely due to uniform OM content and bulk density associated with the low intensity management. Gravimetric soil moisture at field capacity (θ_{WHC}) and saturation (θ_{sw}), followed a trend roughly similar to that of WSA. The Forest site presented high values for both moisture contents (approximately 50% and 60% respectively), the RegG site presented significantly lower values but still high for the textural class (approximately 40% and 48% respectively) and the RegB and Conv significantly lower values (around 30% and 39% respectively). These differences mirror the trends observed in WSA and soil organic matter concentration. The ultimate driver of these appears to be vegetation cover, a key factor controlling soil hydrological properties even within similar soil types (Pachepsky and Park 2015). Although we suggest an improvement in soil water availability for the olives in RegG as compared to RegB and Conv, the absolute magnitude of this potential improvement remains uncertain because only the upper 0–15 cm soil layer was measured. Future studies should assess soil water-related properties throughout the rooting profile to capture the full extent of these effects. Nevertheless, a rough calculation of differences in water content at field capacity (assuming similar bulk density) indicates approximately 20 mm or 200 m^3 ha^{-1}, of additional storage capacity in RegG. This is a not negligible amount in a region where irrigated olive groves use between 1200 and 2000 m^3/ha for the whole season. This increase is comparable to the 187 m^3 ha^{-1} increase in water holding capacity estimated by Nichols (2017) for a 1% rise in soil organic carbon in the top 30 cm. Again, there was a lack of clear differences in these gravimetric moisture content between the under canopy and inter-row areas, which can be explained by the reasons commented for bulk density and WSA. The permanent wilting point (θ_{PWP}) showed notable variation among the different management systems. The highest value was recorded in RegB, exceeding those observed in both the forest and the better performing regenerative orchard (RegG). This result may be related to differences in soil texture, as a higher clay content

TABLE 6 | Comparative economic performance of regenerative and conventional olive grove management systems (2022–2023 campaign).

Task	Conventional (€/ha)	Task	Regenerative (€/ha)
Pruning (AEMO 2023[a]) – (28 h/ha every 2 years)	144.21	Pruning (23 h/ha by professional pruner every 2 years)	116.73
Pruning removal (AEMO 2023[a]) – (14 h farm labourer +0.7 tractor + chipper every 2 years)	85.77	Pruning removal (14 h/ha farm labourer +0.8 h/ha tractor + chipper every 2 years)	87.07
Sucker removal (AEMO 2023[a]) – (6.5 h/ha)	63.28	Sucker removal (3 h/ha farm labourer) – suckers reduced by sheep activity	29.55
Soil maintenance (AEMO 2023[b]) – (no tillage, no vegetation cover + herbicides + brush cutter)	433.51	Soil maintenance (5 h/ha, 2 farm labourers) – no tillage, vegetation cover and intensive grazing with sheep	98.50
Pests and diseases (AEMO 2023[a]) – (2/3 application cost: 74.07 €/ha + products. 2 treatments)	251.81	Pests and diseases (0.8 h/ha, tractor driver + tractor + sprayer) – application of a treatment against the olive fruit fly (4220 kg, 1.60 €/kg), a specific treatment for *Prays oleae* (300 kg, 21.59 €/kg), a spring copper treatment for the control of leaf spot (390 kg, 12.28 €/L), and an additional treatment in summer (174 kg, 13.28 €/L) (ha = 217)	140.20
Fertilisation (AEMO 2023[a]) – (1/3 cost of 3 applications (42.18 €/ha) + foliar fertiliser (K, N) + soil fertiliser/2 years)	248.65	Fertilisation (0.8 h/ha, tractor driver + tractor + sprayer) – foliar application in spring of trace elements and amino acids, another application in summer, and a further post-harvest and autumn application. 285 L in each treatment, 21.79 €/L (ha = 217)	160.99
Irrigation (rainfed)	0	Irrigation (rainfed)	0
Harvesting (AEMO 2023[a] with a reference value of 805 €/ha for a yield of 3500 kg/ha, we consider a yield of 2200 kg/ha)	506	Harvesting (1 trunk shaker operated by a trained operator, four farm labourers using motorised harvesting combs, and four workers managing the collection nets)	848
Certification	0	Certification (€/ha) – 919.56 € for 217 ha	4.24
Total cost (€/ha)	1733.23	Total cost (€/ha)	1485.28
Selling Price (€/kg EVOO), yield of 18.61% (Parras Rosa 2024)	5.93	Selling Price (€/kg EVOO), yield of 18.61% (Parras Rosa 2024)—the 16.4% higher selling price of EVOO compared to the conventional system is attributable to the organic certification of the farm, as well as the additional premium granted by the mill for the implementation of regenerative management practices	6.9
Olive yield (kg/ha)	2200	Olive yield (kg/ha)	2200
Gross income (€/ha)	2427.86	Gross income (€/ha)	2824.99
Net balance income (€/ha)	466.77	Net balance income (€/ha)	1339.72
B:C ratio	1.40	B:C ratio	1.90

Note: B:C denotes the Benefit:Cost ratio, calculated considering only the operational costs presented in this table. Other costs, such as land amortisation, taxes, and similar expenses, are not included, as they are assumed to be identical for both management strategies.
[a]Traditional mechanizable olive groves are rainfed.
[b]No mechanizable.

in RegB likely increased the proportion of fine pores capable of retaining water more tightly. In addition, the greater accumulation of organic matter in regenerative systems can enhance total water retention by increasing microporosity. However, a higher θ_{PWP} does not necessarily imply greater water availability for plants, since part of that water is retained at potentials too high to be absorbed by roots (Saxton and Rawls 2006). The contrasting patterns observed between canopy and inter-row sites

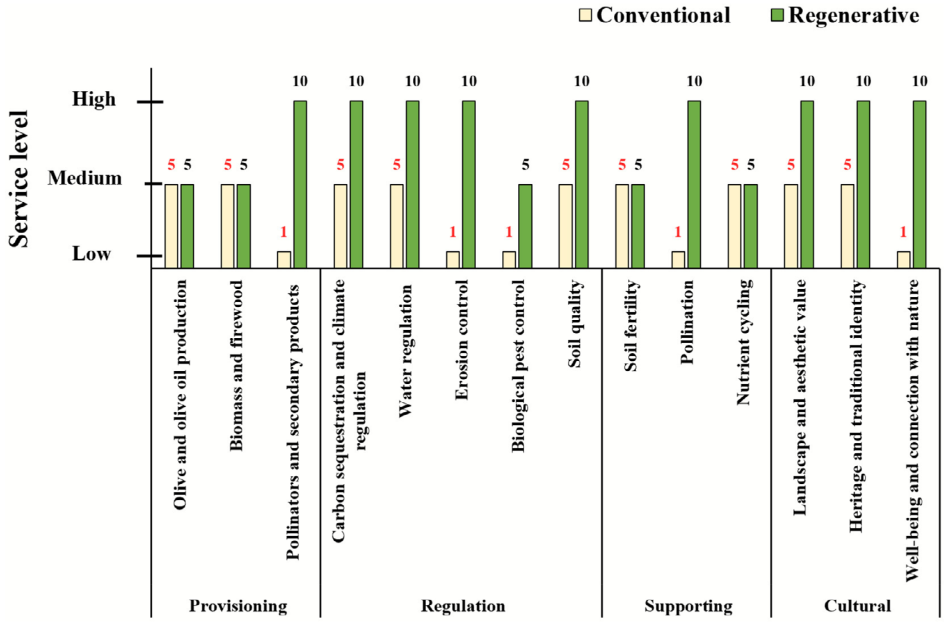

FIGURE 6 | Comparative semi-quantitative assessment of ecosystem service under regenerative and conventional olive grove management.

TABLE 7 | Soil organic carbon stock (SOCS, Mg ha^{-1}) under different systems (regenerative: RegG and RegB, and Conventional) in the top soil (0–15 cm).

Management system			
	Conventional		5.6 ± 1.5b
	Regenerative	RegG	7.9 ± 1.7a
		RegB	5.3 ± 1.2b

Note: Different lowercase letters indicate statistically significant differences ($p < 0.05$) among Conventional, RegG, and RegB sites. One-way ANOVA was used to assess the existence of significant differences.

further suggest the influence of spatial heterogeneity in organic matter inputs and root activity. In RegB, the higher θ_{PWP} under the canopy may reflect greater organic matter accumulation and biological activity associated with the presence of ground cover vegetation, whereas in Conv, the lower θ_{PWP} under the canopy could be related to the absence of ground cover and reduced organic inputs. These results indicate that regenerative practices enhance soil water retention compared with conventional management, likely due to higher organic matter and improved soil structure, although not all retained water is immediately available to plants.

4.2 | Soil Chemical Properties

The most relevant aspect regarding soil organic matter (OM) was the overall high concentration found in the olive sites (in all cases above 4%) and the significant increase in the RegG site as compared to RegB and Conv sites, with an increase from roughly 4% to 7%. These overall high values, which are in the upper range of values measured by previous studies in the region (e.g., Castro et al. 2008; Álvarez et al. 2007; Soriano et al. 2012), can be explained by the low-intensity management of the olive groves and the favourable edaphoclimatic conditions of the area, which promote high OM concentrations in topsoil under undisturbed Mediterranean conditions. This is highlighted by the 13.5% soil OM measured in the Forest site, above the 10.8% reported by Álvarez et al. (2007) in a cambisol soil ' or the 10.6% reported by Soriano et al. (2012) in a regosol soil type. Regenerative management demonstrated the potential to substantially increase OM levels, even in soils already rich in organic matter, though its effects were not uniform across groves. This highlights the capacity of regenerative practices to enhance soil carbon sequestration under these conditions. However, as with soil water availability, further research is needed to assess OM changes at deeper soil layers and to better understand the heterogeneity observed between RegG and RegB. Additionally, we observed within-grove differences in topsoil OM between under canopy and inter-row zones (an issue also noted by Gómez et al. 2022) suggesting the importance of accounting for this spatial variability when monitoring soil organic carbon stocks. Higher OM levels in the inter-row areas are mainly associated with carbon inputs derived from cover crop biomass and surface residues (Vicente-Vicente et al. 2016), whereas under-canopy zones receive carbon primarily from rhizodeposition and litterfall, which are more decomposed and less incorporated due to shading and lower microbial activity (Six et al. 2002). The limited herbaceous growth under the canopy may also restrict microbial diversity and organic matter stabilisation processes (Tiemann et al. 2015). The spatial variation in OM between canopy and inter-row positions reflects differences in carbon input sources and soil surface conditions. Future research should quantify these fluxes to better link vegetation structure and management practices to spatial patterns of soil carbon storage in olive groves.

Macronutrient concentration in soil, organic N and extractable P and K, followed a trend similar to that of OM concentration, albeit with slight changes depending on the nutrient. Overall soil organic N concentration was high in all the sites according to reference values for olives (e.g., Gómez, Álvarez, and Soriano 2009), with relative differences paralleling those of OM, which is expected given their close relationship. These high values likely result from moderate grove productivity (limiting N export), inputs from regenerative practices (e.g., legumes) and efficient internal nutrient cycling, particularly in RegG. Extractable K levels were also high, partly due to the soil's marine sedimentary origin, as reflected in the Forest site (> 1000 mg/kg). Although K levels were lower in olive groves, they remained high according to agronomic thresholds (Gómez, Álvarez, and Soriano 2009), sustained by both edaphic background and positive nutrient balances. Again, RegG showed higher N and K concentrations than RegB, underscoring the potential to improve nutrient availability and soil quality through better implementation of regenerative practices, particularly by increasing vegetation cover in groves such as RegB. Differences were more pronounced for extractable P, the Forest site showed moderately high natural P levels, while RegG displayed similar concentrations, suggesting a balanced and sustainable P cycle. In contrast, RegB showed lower P values, near the threshold for adequate olive cultivation (Gómez, Álvarez, and Soriano 2009), likely due to limited biomass production, reduced grazing activity (and associated manure inputs) and increased P loss through runoff and erosion from bare areas, phenomena reported in other studies (e.g., Gómez-Muñoz et al. 2016). These results suggest that regenerative management in sites like RegB should focus on increasing ground cover and regulating sheep grazing to promote uniform vegetation distribution, but with lower intensity than in RegG. In the Conv site, P concentration was high under canopy area, corresponding to localised fertilisation, while inter-row values were similar to those in RegB, confirming the spatial heterogeneity induced by conventional practices. Estimated cation exchange capacity (CEC) values for all the sites were high compared to values reported for similar olive-growing soils (e.g., Gómez, Álvarez, and Soriano 2009) and can be explained by edaphogenesis of the soils in the study area and high nutrient and soil OM already described and discussed. A similar pattern was observed for soil Ca, Na and electrical conductivity (EC), which were high but remained within suitable ranges for olive cultivation (García et al. 2004).

4.3 | Soil Biological Properties

As in the case of some other physical (WSA) and chemical (OM) soil properties, the four soil biological properties evaluated including soil metabolic activity as measured by the Biolog Ecoplates by the AUCAWCD, the Shannon diversity index H′, the culturable bacterial populations as measured by the number of CFU and the richness; presented a clear ranking among the study sites. The Forest site presented high values of these four biological indicators according to previous studies studying natural reference areas nearby olive groves, for example, CFU in Soriano et al. (2012). As expected, the Conv site exhibited significantly lower biological activity and diversity compared to the Forest site and the regenerative orchard, confirming findings from previous work (e.g., Gómez, Álvarez, and Soriano 2009; Montes-Borrego et al. 2013). However, a key result of this study is that the regenerative sites showed a substantial and statistically significant increase in all four biological indicators compared to the Conv site, despite the Conv site already presenting relatively high values when compared with typical olive groves in the region. This consistency further supports the notion that regenerative practices improve soil biological quality consistently across grove areas, not just locally. This agrees with the systematic meta-analysis by Lori et al. (2025), who found that sustainable agricultural management generally enhances soil biota abundance, microbial biomass and enzymatic activity compared to conventional practices. Similarly, García-Orenes et al. (2010) reported higher microbial biomass and activity under organic and reduced-tillage systems in semiarid Mediterranean agroecosystems.

The results of the heatmap analysis reveal that soil microbial communities respond differently depending on the type of agricultural management to which they are exposed. Specifically, it was observed that the Conv site, along with the RegB inter-row, share a distinct carbon substrate utilisation pattern compared to the remaining regenerative sites and Forest. This suggests that conventional management practices tend to shape microbial communities in similar ways, which differ functionally from those formed under regenerative approaches. This divergence may be due to the more intensive use of chemical inputs and reduced vegetation cover commonly associated with conventional systems, which could be limiting both the diversity and functional capacity of soil microbial communities. As a result, these communities may utilise a narrower or different range of organic compounds. Comparable patterns have been documented in Mediterranean systems where management intensity affects microbial community composition and activity (Longa et al. 2017; De Corato 2020). Furthermore, increased plant diversity has been shown to stimulate soil microbial activity and carbon storage, enhancing belowground ecosystem functioning (Lange et al. 2015). A similar pattern is evident in the RegB treatment, where reduced ground cover appears to be associated with a microbial profile closer to Conv site. This finding highlights the need to intensify regenerative practices in certain areas of the regenerative farm (such as RegB) in order to foster a gradual transition toward the more desirable functional profiles observed in treatments like RegG. According to Hartmann et al. (2015), long-term organic and reduced-input systems maintain distinct and diverse microbial communities due to higher vegetation cover and organic matter inputs. Likewise, Schmidt et al. (2018) and Tautges et al. (2019) demonstrated that cover cropping and no-till practices enhance microbial diversity, stability and carbon sequestration, which contribute to long-term soil ecosystem resilience.

Soils under regenerative management show more consistent patterns of carbon utilisation among themselves and greater similarity to forest soil, which may reflect higher microbial diversity and more complex and efficient soil ecosystem functioning. This is likely due to practices that promote vegetation cover, root diversity and continuous organic matter input. These observations are consistent with Lupatini et al. (2017), who found that organic systems support more heterogeneous and functionally diverse soil microbiota than conventional ones and with Bender et al. (2016), who emphasised that biodiversity acts as an engine for soil ecological engineering and agricultural sustainability.

The principal component analysis further supports these observations, showing a clear separation between regenerative and conventional treatments. This distinction confirms that soil management practices directly influence how microbial communities metabolise organic matter, ultimately affecting their ecological function and the overall health of the soil. Overall, these findings indicate that regenerative practices, characterised by reduced soil disturbance, increased vegetation cover and enhanced organic inputs, foster more diverse and functionally active microbial communities. Consistent with Lori et al. (2017), García-Orenes et al. (2010) and Bender et al. (2016), these results reinforce that practices promoting biodiversity, organic matter inputs and minimal disturbance lead to measurable improvements in microbial activity, soil functionality and agroecosystem sustainability. These results are also consistent with previous studies, such as Hartmann et al. (2015), who reported greater microbial diversity under organic management compared to conventional systems. Similarly, Lupatini et al. (2017) showed that organic systems support a more functionally diverse and heterogeneous soil microbiota. Additionally, LaCanne and Lundgren (2018) linked regenerative management with both ecological and economic benefits, including improvements in soil microbial health.

4.4 | Leaf Nutrient Content

Overall, the concentrations of the different micro and macronutrients in leaves were within the optimal range for cultivated olives (e.g., García et al. 2004; Sibbett and Ferguson 2005), albeit in the lower range of the recommended ones for N and P. This closeness to adequate threshold values can explain the lack of visual symptoms or nutrient deficiency in leaves or the apparent lack of concern by the farm owners in relation to fruit yield. The relatively low nutrient levels could reflect those standard recommendations are based on higher yielding groves with greater nutrient demands and often poorer soils. Thus, the nutritional thresholds used as reference may not fully align with the actual requirements of the low input, moderate yield systems assessed in this study.

Differences in leaf nutrient concentration of Fe, Cu, Mn and B among sites cannot be attributed to a combination of different fertilisation and management practices and we can only speculate on the relative weight of each set of practices in these differences, which is beyond the scope of our study that was to identify the overall nutritional status of the olive trees in both groves and sites.

4.5 | Assessment of Ecosystem Services Under Different Management Practices

The results demonstrate that regenerative agricultural management substantially enhances the multifunctionality of agroecosystems, improving their capacity to provide ecological, productive and socio-cultural benefits simultaneously. The significant increase in regulating services (45 vs. 17) indicates that regenerative practices, such as cover cropping, pruning residues and organic amendments, foster improvements in soil carbon sequestration, structure and water regulation, consistent with previous findings (Lal 2020; Sher et al. 2024). These practices enhance soil porosity and organic matter accumulation, thereby reducing erosion and improving climate regulation functions. Similarly, the higher values in supporting services (20 vs. 11) suggest that regenerative management strengthens the ecological processes underpinning long-term productivity, including pollination and nutrient cycling. Increased vegetation cover, biodiversity and reduced chemical inputs contribute to the maintenance of soil fertility and resilience (Nicholls and Altieri 2018). The most pronounced difference was observed in cultural services (30 vs. 11), which indicates that regenerative management not only benefits ecological performance but also provides socio-cultural and aesthetic co-benefits. The enhancement of landscape aesthetics, heritage identity and human–nature connection suggests that regenerative systems foster stronger social acceptance and emotional engagement with agricultural landscapes. These outcomes align with the findings of Gosnell et al. (2019), who emphasise the role of regenerative practices in promoting both ecological restoration and community well-being. Conversely, the consistently lower scores of the conventional system across all categories reflect its focus on short-term productivity at the expense of ecological regulation and social value. Overall, these results reinforce the notion that regenerative agriculture supports a more balanced and resilient provision of ecosystem services, integrating productivity with environmental sustainability and cultural enrichment. Such multifunctionality positions regenerative management as a viable strategy for transitioning toward sustainable agroecosystems in Mediterranean olive production systems and beyond.

Within the supporting and regulating service categories, the significantly higher soil organic carbon stock (SOCS) observed under the RegG management system suggests that improved vegetation cover plays a key role in enhancing soil carbon accumulation (Vicente-Vicente 2017; Torrús-Castillo et al. 2022). The increase in soil organic carbon under cover crops is not solely attributable to annual carbon inputs from plant residues. Reduced erosion and the presence of diverse spontaneous vegetation enhance microbial processing and stabilisation of organic matter, introducing a wider range of carbon compounds, some of which are more resistant to decomposition (Gómez, Guzmán, et al. 2009; Tiemann et al. 2015). Therefore, systems with continuous or more diverse vegetation cover tend to accumulate higher levels of soil organic carbon due to increased biomass inputs and improved microclimatic and microbial conditions (e.g., Lal 2020; Poeplau and Don 2014). Moreover, regenerative management practices that maintain spontaneous or adventitious vegetation have been shown to enhance soil structure and microbial activity, promoting carbon stabilisation within soil aggregates (Six, Paustian, et al. 2000; A. J. Franzluebbers 2010). In contrast, the lower SOCS values found under RegB and Conv are likely associated with reduced vegetation density and the presence of bare soil patches or the absence of cover crops, which expose the soil to higher oxidation rates and limit organic matter incorporation.

Overall, the findings indicate that management practices promoting continuous ground cover and reduced soil disturbance, such as those in RegG, can substantially improve soil carbon sequestration. This, in turn, strengthens supporting and regulating ecosystem services, contributing to greater soil resilience and long-term sustainability.

4.6 | Comparative Economic Analysis of Management Practices

The regenerative system exhibited a higher selling price, reflecting the added value associated with superior product quality and the sustainable practices implemented. It is important to highlight that the selling price of olives under regenerative management is higher because this system operates under organic certification and the oil mill provides an additional premium for plots managed using regenerative practices. The benefit–cost ratio was also greater in the regenerative system (1.90) compared to the conventional system (1.40), indicating that for every euro invested, regenerative management generates 1.90 € in return, whereas the conventional system barely covers its production costs.

The regenerative system substantially reduces expenses related to soil maintenance, fertilisation and pest and disease control, as no tillage is performed and no chemical products are used (with the exception of kaolin, which is prepared by the farmer). In contrast, the conventional system incurs higher costs in these areas. A notable difference is also observed in sucker removal: under regenerative management, olive suckers are controlled through sheep grazing, whereas in the conventional system, hired labor is required for manual removal using axes and herbicide applications. Harvesting costs are higher in the regenerative system due to the challenging orography and steep slopes of the terrain, which require additional labor and time, as the harvesting process becomes more difficult under these conditions. Nevertheless, regenerative management proves to be more profitable and sustainable overall, as it combines lower operational costs with improved economic returns. Furthermore, its practices promote soil conservation, biodiversity enhancement and greater agroecosystem resilience, establishing it as an economically viable and environmentally responsible alternative to conventional olive cultivation. It is important to note that, in this case, the regenerative alternative offers both cost reduction and increased profitability. However, this model is feasible due to the efficient integration of pre-existing livestock activity in the area, a condition that may not be scalable or applicable to other regions where livestock farming is not technically or economically viable.

5 | Conclusion

Regenerative management in low intensity olive groves under favourable edaphoclimatic conditions led to significant improvements in key soil health indicators compared to conventional management, resulting in values in the upper range of those described for organic olive orchards in the region. Notable increases were observed in water-stable aggregates, soil moisture at field capacity, soil organic matter, extractable potassium and culturable microorganisms, by approximately 33%, 33%, 75%, 46% and 18%, respectively. In some parameters, such as extractable phosphorus or microbial diversity, values approached those of a nearby natural forest, highlighting the potential of regenerative practices to restore soil functionality. However, differences within the regenerative orchard itself, particularly between areas with contrasting vegetation cover, indicate that optimising ground cover, including adaptive grazing management, is crucial to ensure homogeneous soil benefits.

Beyond improvements in soil health, regenerative management also enhanced soil organic carbon stocks, ecosystem service provision (especially regulating and cultural services) and economic performance, achieving lower costs and a higher benefit–cost ratio than conventional management. These outcomes demonstrate that regenerative agriculture can simultaneously improve soil quality, ecological functionality and farm profitability in Mediterranean olive systems.

While the findings are promising, the study was limited to two adjacent groves under similar environmental conditions. Future research should validate these findings across broader Mediterranean contexts, soil depths and time scales to assess long-term impacts on carbon sequestration, ecosystem resilience and sustainability.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Ancillary data corresponding to the figures and tables will be available in Digital CSIC: https://doi.org/10.20350/digitalCSIC/17408.

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